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# Task Order 221
# CASE STUDIES: TIME REQUIRED TO MATURE AERONAUTIC TECHNOLOGIES TO OPERATIONAL READINESS


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# Table of Contents


**1.0 INTRODUCTION ........ 1**

1.1 Background ........ 1
1.2 Technology Readiness Level (TRL) Definition ........ 1
1.3 Methodology ........ 1

**2.0 METHODOLOGY ........ 3**

2.1 NASA Coordination ........ 3
2.2 Candidate Technology List Development ........ 3
2.3 NASA Interviews and Supporting Documents ........ 3
2.4 Industry Interviews ........ 4

**3.0 SURVEY RESULTS ........ 5**

3.1 Analysis of Results ........ 10
3.2 Maturation from TRL 1 to TRL 9: Overall Sample Statistics ........ 10
3.3 Transition from TRL 1 to TRL 9: Sample Subgroup Statistics ........ 10
3.4 Transition Times between TRLs, for Technologies Reaching TRL 9: Overall Statistics Sample ........ 13
3.5 Transition Times between TRLs for Technologies Reaching TRL 9: Sample Subgroup Statistics ........ 14
3.6 Transition from TRL 1 to TRL 6: Overall Sample Statistics ........ 17
3.7 Transition from TRL 1 to TRL 6: Sample Subgroup Statistics ........ 18
3.8 Transition Times between TRLs, for Technologies Reaching TRL 6 Overall Statistics Sample ........ 20
3.9 Transition Times between TRLs for Technologies that reached TRL 6: Sample Subgroup Statistics ........ 21

**4.0 Findings and Implications of Results for NASA Systems Studies ........ 25**

Bibliography ........ 27

Appendix A – NASA Questionnaire ........ A - 1
Appendix B – Industry Questionnaire ........ B - 1

# Table of Tables

Table 1.2 - 1 Generic/Notional TRL Definitions .............................................. 2
Table 3.1 - 1 Time Required for 19 NASA Technologies to Make Transition from TRLs 1 through 5 to TRL 6 .............................................. 6
Table 3.1 - 2 Time Required for 19 NASA Technologies to Make Transition from one TRL to the Next TRL, up to TRL 6 .............................................. 7
Table 3.1 - 3 Time Required for 12 NASA Technologies to Make Transition from TRLs 1 through 8 to TRL 9 .............................................. 8
Table 3.1 - 4 Time Required for 12 NASA Technologies to Make Transition from one TRL to the Next TRL, up to TRL 9 .............................................. 9
Table 3.2 - 1 Sample Statistics for Twelve NASA Technologies Maturing from TRL 1 to TRL 9 .............................................. 10
Table 3.3 - 1 Sample Statistics for Twelve NASA Technologies Making Transition from TRL 1 to TRL 9, by Type of Aeronautics Technology – Airframe and Flight Systems .............................................. 11
Table 3.3 - 2 Sample Statistics for Twelve NASA Technologies Making Transition from TRL 1 to TRL 9, by Type of Aeronautics Technology – Ground Systems and Propulsion .............................................. 12
Table 3.3 - 3 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 9, by Program Goal or Primary Benefit .............................................. 12
Table 3.3 - 4 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 9 – Focused Program/NASA Tested Technologies .............................................. 13
Table 3.3 - 5 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 9 – Requiring Enabling or New Technologies .............................................. 13
Table 3.4 - 1 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies That Reached TRL 9 .............................................. 14
Table 3.5 - 1 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Technology Type – Airframe and Flight Systems .............................................. 15
Table 3.5 - 2 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Technology Type – Ground Systems and Propulsion .............................................. 16
Table 3.5 - 3 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Program Goal or Primary Benefit .............................................. 16
Table 3.5 - 4 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Focused Program/NASA Tested Technologies .............................................. 17
Table 3.5 - 5 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, for Technologies Requiring Enabling or New Technologies .............................................. 17
Table 3.6 - 1 Sample Statistics for Eighteen NASA Technologies Making Transition from TRL 1 to TRL 6 .............................................. 18
Table 3.7 - 1 Sample Statistics for Eighteen NASA Technologies Making Transition from TRL 1 to TRL 6, by Technology Type – Airframe and Flight Systems... 19

Table 3.7 - 2 Sample Statistics for Eighteen NASA Technologies Making Transition from TRL 1 to TRL 6, by Technology Type – Ground Systems and Propulsion ........ 19
Table 3.7 - 3 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 6, by Program Goal or Primary Benefit ........ 19
Table 3.7 - 4 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 6 – Focused Program/NASA Tested Technologies ........ 20
Table 3.7 - 5 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 6 – Requiring Enabling or New Technologies ........ 20
Table 3.8 - 1 Sample Statistics for Transition Times between TRLs, for Eighteen NASA Technologies That Reached TRL 6 ........ 21
Table 3.9 - 1 Sample Statistics for TRL to TRL Trends for Eighteen NASA Technologies Reaching TRL 6, by Technology Type – Airframe and Flight Systems ........ 22
Table 3.9 - 2 Sample Statistics for TRL to TRL Trends for Eighteen NASA Technologies Reaching TRL 6, by Technology Type – Ground Systems and Propulsion ........ 22
Table 3.9 - 3 Sample Statistics for TRL to TRL Trends among Eighteen NASA Technologies Reaching TRL 6, by Program Goal or Primary Benefit ........ 23
Table 3.9 - 4 Sample Statistics for TRL to TRL Trends among Eighteen NASA Technologies Reaching TRL 6 – Focused Program/NASA Tested Technologies ........ 23
Table 3.9 - 5 Sample Statistics for TRL to TRL Trends among Eighteen NASA Technologies Reaching TRL 6 – Technologies Requiring Enabling or New Technologies ........ 23

## Table of Figures

Figure 3.2 - 1 Transition Trajectory Statistics, TRL 1 to TRL 9, for Twelve NASA Technologies ........ 11
Figure 3.4 - 1 Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9 ........ 15
Figure 3.6 - 1 Transition Trajectory Statistics, TRL 1 to TRL 6, for Eighteen NASA Technologies ........ 18
Figure 3.8 - 1 TRL to TRL Transition Trajectory Statistics, TRL 1 to TRL 6, for Eighteen NASA Technologies ........ 21

# Executive Summary

The Systems Analysis Branch at NASA Langley Research Center is part of an inter-center analysis team responsible for providing an annual assessment of potential impacts of NASA technologies on the national aerospace goals outlined in the Aeronautics & Space Transportation Technology: Three Pillars for Success. As a part of this effort, this task investigated how long it takes for technologies to go from an initial concept to marketable product, based on NASA defined technology readiness levels (TRLs).

To demonstrate this, a "Years to TRL" matrix was developed for selected NASA technologies. The matrix was developed through literature reviews, interviews with relevant NASA personnel and interviews with industry personnel. The technologies investigated for the matrix were eighteen civil aeronautics products from the major aeronautic technology divisions of airframes, propulsion, flight systems, and ground systems.

In addition to an overall "Years to TRL" matrix, matrices of maturation times were developed for subgroups of NASA technologies. These subgroup matrices examined the relationships between technology maturation and the following characteristics: the technology division, the primary goal or benefit to be derived from implementing the technology, whether the technology was a part of a NASA focused program, and whether the technology required NASA testing or some sort of enabling or new technologies.

Statistical analysis of the overall matrix shows that there is considerable variability in the time it takes for technologies to mature. Analysis of the subgroups indicates that these average maturation times vary by technology type, by the technology's primary benefit or goal, and, to a lesser extent, by the need for additional technologies or NASA testing for the successful maturation of the technology.

The influence of research intensity, funding changes, and the socio-political environment on the development speed for any given technology were not considered in this effort, but research into the investigated technologies revealed that these issues do matter. It was also found that existing models and templates for assessing the progress of NASA technology development – such as the TRL framework – do not have universal acceptance, and that developing a consensus model for the stages of NASA research may be difficult, although such a model may facilitate future efforts to assess research progress within NASA programs.

# 1.0 INTRODUCTION

## 1.1 Background

The Systems Analysis Branch at NASA Langley Research Center is part of an inter-center analysis team. A responsibility of the team is to provide an annual assessment of potential impacts of NASA technologies on the national aerospace goals outlined by the Alliance Development Office in their document Aeronautics & Space Transportation Technology: Three Pillars for Success. The assessment process is structured such that technology benefits are credited toward a goal when a technology is ready for operational use. Thus, technology impacts are projected to occur at the end of the time period required to assure its operational readiness. Therefore, a means of projecting operational readiness for NASA technologies needs to be developed to assess the potential impacts on national aerospace goals. As a part of this effort, this task is an investigation into how long it has taken for technologies to go from the initial concept to marketable product, based on nine technology readiness levels (TRL) defined by NASA (section 1.2).

This is accomplished through a series of case studies on selected technologies to provide guidelines for estimating the time required to mature different technologies to the point of operational readiness. The product of this task will be a matrix, backed by all supporting data, of technology types by current TRL levels with each cell containing the estimated time required to mature the technology to a TRL of 9.

## 1.2 Technology Readiness Level (TRL) Definition

The Technology Readiness Level (TRL) is a scale used to reflect the maturity of a technology and how much is known about the technology's potential impacts. The TRL scale is technology independent. For all technologies, a TRL of 1 indicates that the technology has not begun testing and a TRL of 9 relates to the stage that verification and validation of the technology is complete and the technology is ready for operational use. Table 1.2 - 1 defines the generic/notational TRL definitions.

NASA typically works on technologies from a TRL of 1 to a TRL of 6. At TRL 6, industry often takes the technology and develops it to the state of operational readiness, TRL 9. Once a technology reaches a TRL of 9 industry either turns the technology into a marketable product or uses it in the development of other technologies. An example of the later is the use of computer codes for the testing and design of engines.

## 1.3 Methodology

The task was divided into four subtasks. First was to develop list of candidate technologies for the case study investigation. The candidate technology list was developed with input from NASA Headquarters and three NASA Research Centers,

**Table 1.2 - 1 Generic/Notional TRL Definitions**

| | Level | Qualifier/Development Hurdle |
|---|---|---|
| Basic Research | 1 | Basic scientific/engineering principles observed and reported |
| Feasibility Research | 2 | Technology concept, application, and potential benefits formulated (candidate system selected) |
| Feasibility Research | 3 | Analytic and/or experimental proof-of-concept completed (proof of critical function or characteristic) |
| Technology Development | 4 | System concept observed in laboratory environment (breadboard test) |
| Technology Development | 5 | System concept tested and potential benefits substantiated in a controlled relevant environment |
| System Development | 6 | Prototype of system concept is demonstrated in a relevant environment |
| System Development | 7 | System prototype is tested and potential benefits substantiated more broadly in a relevant environment |
| Operational Verification | 8 | Actual System constructed and demonstrated, and benefits substantiated in a relevant environment |
| Operational Verification | 9 | Operational use of actual system tested, and benefits proven |

Langley, Glenn, and Ames. Technologies under consideration were those that have been applied to civil aeronautics products that included technology types from the major aeronautic technology divisions of airframes, engines, and systems (section 2.2). Meetings at the three centers identified specific technologies and contacts who could provide input to the case history and TRL development of each candidate technology. The final technology selection was coordinated through the NASA Intercenter Analysis Team.

The second subtask consisted of a literature review and interviews with the NASA personnel identified in subtask 1. Through these interviews a timeline for each technology was developed for each TRL step while the technology was at NASA.

Subtask 3 was interviews conducted with those industries or organization that have adopted the technologies identified in subtask 2. The purpose of these interviews was to determine the time required to mature the technology from the stage at which it was received from NASA to TRL 9.

The final subtask is a completed “Years-to-TRL” matrix and a technical memorandum that reports on the candidate technologies and the results of the NASA industry interviews.

# 2.0 METHODOLOGY

## 2.1 NASA Coordination

Coordination meetings were held at NASA Langley, Glenn, Ames, and Headquarters to introduce the study team and to identify those technologies related to civil aeronautics products applicable to this study. Those who attended were selected because they were familiar with a specific NASA program or who knew of those who were. They recommended specific technologies and provided contact names for the NASA interviews.

## 2.2 Candidate Technology List Development

The first step was to develop a list of candidate technologies for study. The selected technologies would be used as case studies to provide guidelines for estimating the time required to mature technologies to the point of operational readiness. Technologies under consideration were those that have been applied to civil aeronautics products.

In order to select the candidate technologies, meetings were held at NASA Headquarters and three NASA centers: Langley, Glenn and Ames. At each meeting NASA personnel in attendance recommended technologies they thought would make good candidates for study. They also supplied contact information for the NASA interviews that would take place in the second step of the task. After these meetings were conducted, NASA Langley's inter-center analysis team along with SAIC and GRA, Inc., reviewed the technology recommendations and selected the final technologies list. Selections included technology types from the major aeronautic technology divisions of airframes, engines and systems. The technologies selected were:

- Carbon-6 Thermal Barrier
- Direct To
- Electro-Expulsive Deicing
- Engine Monitoring Systems
- Flow Visualization
- Fly-by-Light
- GA Wing
- Low Emissions Combustors
- Nondestructive Evaluation
- Particulate Imaging Velocimetry (PIV)
- Propfan Development
- Runway Grooves
- Supercritical Wing
- Surface Movement Advisor SMA
- Tailless Fighter
- Thrust Vectoring Nozzle
- Tiltrotor Technology
- Tribology

## 2.3 NASA Interviews and Supporting Documents

Once the technologies were selected the study team contacted NASA personnel identified as an authoritative source of information about that technology. A questionnaire was developed to define and standardize the data collected. A copy of this questionnaire is shown in appendix A. The questionnaire focused on the history and applicability of the technology and how long it took to achieve the TRL levels. The individuals were first contacted by telephone. If the original contact was not the correct one he/she usually provided a more appropriate selection. Most of the questionnaires were filled out over the phone. Sometimes the questionnaire was faxed or emailed to the individual so that he/she could fill it out and return it.

Each interviewee was also asked for written information, reports, fact sheets, etc., that described the development of the technology. Not all contacts knew of, or provided, supporting material. The interview team also performed internet searches of NASA center libraries for supporting material on the specific technology. However, in some cases, the interview team was not able to obtain supporting data for the technologies.

## 2.4 Industry Interviews

Each NASA interviewee was asked to provide contacts at the appropriate agency or industry to which the technology was given for final development. An industry questionnaire was developed for these interviews and is shown in appendix B.

Many of the selected technologies reached TRL 9. Some did not reach TRL 9, or had not yet reached that level, and some technologies did not go beyond NASA development. For example, one is being employed by the Federal Aviation Administration (FAA) at the level at which it was tested. Some were provided to industry but final development is not expected for several years. Furthermore, not all of the suggested industry contacts were available. Some had left their employer and could not be reached at their new locations. Follow-up with the NASA contacts could not provide alternative contacts or suggestions. Due to this, industry data was not available for every technology. When industry data was not available on TRL 7 through TRL 9 accomplishments, data developed in interviews with NASA researchers was used for the TRL7/TRL 9 dates.

## 3.0 SURVEY RESULTS

The interviews conducted during the survey process are a source of multifaceted information on past NASA research undertakings. As reflected in the interview forms, the analysis of research project chronologies can be split into groups and subgroups in a variety of ways, including:

- What type of aeronautics technology did the research advance?
- Did successful development of the technology require other enabling technologies or the development of some other new product?
- What primary need or benefit did the technology under development fulfill?
- Was the technology developed under a NASA focused program?
- Did NASA conduct testing of the new technology?

The interviews provided data for the progression of eighteen technologies from a TRL of 1 to a TRL of 6, and of twelve technologies (all of which are among the eighteen TRL 1 to 6 technologies) from a TRL of 1 to a TRL of 9. The twelve TRL 1 to 9 technologies in the list are marked with an *. The eighteen TRL 1 to 6 technologies include:

- **Carbon-6 Thermal Barrier** – braided carbon-fiber thermal barrier for use in solid fuel rocket motor nozzle joints
- **Electro-Expulsive Deicing *** – in-flight non-mechanical critical surface ice clearing system
- **Engine Monitoring Systems *** – “intelligent” display of engine performance factors
- **Flow Visualization *** – computer and graphical simulation of air flow around aircraft
- **GA Wing *** – Advanced General Aviation wing, with improved laminar flow and stall/spin resistant wing tip design
- **Supercritical Wing *** – more efficient wing design
- **Tiltrotor Technology *** – aircraft with characteristics of both rotary winged aircraft and fixed wing aircraft
- **Propfan Development *** – new engine design using fewer blades also known as unducted fan, open rotor, or ultra high bypass engine
- **Nondestructive Evaluation** – crack, corrosion, and disbanding detection without disrupting or disturbing aircraft surfaces or structures
- **Fly-by-Light *** – replacement of electronic sensors and data transmitters and mechanical control links with optical components and subsystems
- **Particulate Imaging Velocimetry PIV *** – measure and analyze gas velocity inside engines
- **Tailless Fighter** – agile fighter design for National Security needs
- **Thrust Vectoring Nozzle** – provide guidance control on tailless aircraft
- **Surface Movement Advisor SMA *** – improved monitoring and control of aircraft surface movement at airports
- **Runway Grooves *** – transverse channels or slots in runway surface to improve aircraft braking performance
- **Low Emissions Combustors** – two stage combustors with double-annular dome, shingle liners, and multiple passage prediffusers
- **Direct To** – improve aircraft flight path efficiency
- **Graphite Fiber Stator Vane Bushings (Tribology) *** -- lubrication

The raw material for analysis in Table 3.1 - 1, Table 3.1 - 2, Table 3.1 - 3, and Table 3.1 - 4 show TRL transition values for each of these technologies. The tables also indicate relevant characteristics of each technology's development process. The individual interviews from which the tabulated information has been taken are collected appendix B of this report.

**Table 3.1 - 1 Time Required for 19 NASA Technologies to Make Transition from TRLs 1 through 5 to TRL 6**

| Name of Technology | Carbon-6 Thermal Barrier | Electro Expulsive DeIcing | Engine Monitoring Systems | Flow Visualization | GA Wing | Supercritical Wing | Tiltrotor Technology | Graphite Fiber Stator Vane Bushings (Tribology) | Propfan development | Fiber Preform Seal | Nondestructive Evaluation | Fly-by-Light | Particulate Imaging Velocimetry | Tailless Fighter | Thrust Vectoring Nozzle | Surface Movement Advisor | Runway Grooves | Low Emissions combustors | Direct To |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years to TRL 6 from TRL: | | | | | | | | | | | | | | | | | | | |
| 1 | 1.9 | 4 | 3 | 11 | 5 | 5.5 | 28 | 10 | 8.5 | 11.5 | 4.5 | 20.5 | 12 | 8 | 5 | 2.1 | 1.5 | 10 | 1.6 |
| 2 | 1.5 | 3.5 | 2.5 | 6 | 4.5 | 4 | 25 | 8 | 6 | 10.5 | 4 | 18 | 10 | 5 | 4.7 | 1.3 | 0.8 | 9 | 1.4 |
| 3 | 1.1 | 3 | 2 | 5 | 4 | 3 | 24 | 6 | 5 | 9 | 3 | 13 | 6 | 4 | 4.4 | 1 | 0.6 | 7 | 1.3 |
| 4 | 0.7 | 2 | 1.5 | 1.5 | 3.5 | 2 | 23 | 4 | 3.5 | 7.5 | 2 | 5.5 | 3.5 | 3 | 4 | 0.7 | 0.4 | 6 | 1.2 |
| 5 | 0.2 | 1 | 1 | 0.5 | 0.5 | 1 | 22 | 2 | 1 | 6 | 1 | 1.5 | 0.5 | 2 | 2 | 0.35 | 0.2 | 4 | 0.1 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | | | | | | | | | | |
| Criteria A | 4 | 2 | 2 | 2 | 1 | 1 | 2 | 4 | 4 | 4 | 1 | 2 | 4 | 2 | 2 | 3 | 3 | 4 | 3 |
| Criteria B | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| Criteria C | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 2 | 1 | 3 | 6 | 6 | 1 | 2 | 3 | 3 |
| Criteria D | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| Criteria E | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| Criteria F | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |

Criteria A, Type of Technology: 1 = Airframe, 2 = Flight Systems, 3 = Ground Systems, 4 = Propulsion
Criteria B, Enabling Technology Needed: 0 = No, 1 = Yes
Criteria C, Primary Goal/Benefit: 1 = Cost Reduction, 2 = Safety, 3 = Performance
Criteria D, Focused Program: 0 = No, 1 = Yes
Criteria E, New Product Needed: 0 = No, 1 = Yes
Criteria F, NASA Tesgint: 0 = No, 1 = Yes

## Table 3.1 - 2 Time Required for 19 NASA Technologies to Make Transition from one TRL to the Next TRL, up to TRL 6

| Name of Technology | | Carbon-6 Thermal Barrier | Electro Expulsive DeIcing | Engine Monitoring Systems | Flow Visualization | GA Wing | Supercritical Wing | Tiltrotor Technology | Graphite Fiber Stator Vane Bushings (Tribology) | Propfan development | Fiber Preform Seal | Nondestructive Evaluation | Fly-by-Light | Particulate Imaging Velocimetry | Tailless Fighter | Thrust Vectoring Nozzle | Surface Movement Advisor | Runway Grooves | Low Emissions combustors | Direct To |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | | | | | | | | | | | | | | | | | | | | |
| from TRL | to TRL | | | | | | | | | | | | | | | | | | | |
| 1 | 2 | 0.4 | 0.5 | 0.5 | 5 | 0.5 | 1.5 | 3 | 2 | 2.5 | 1 | 0.5 | 2.5 | 2 | 3 | 0.3 | 0.8 | 0.7 | 1 | 0.2 |
| 2 | 3 | 0.4 | 0.5 | 0.5 | 1 | 0.5 | 1 | 1 | 2 | 1 | 1.5 | 1 | 5 | 4 | 1 | 0.3 | 0.3 | 0.2 | 1 | 0.1 |
| 3 | 4 | 0.4 | 1 | 0.5 | 3.5 | 0.5 | 1 | 1 | 2 | 1.5 | 1.5 | 1 | 7.5 | 2.5 | 1 | 0.4 | 0.3 | 0.2 | 1 | 0.1 |
| 4 | 5 | 0.5 | 1 | 0.5 | 1 | 3 | 1 | 1 | 2 | 2.5 | 1.5 | 1 | 4 | 3 | 1 | 2 | 0.35 | 0.2 | 2 | 1.1 |
| 5 | 6 | 0.2 | 1 | 1 | 0.5 | 0.5 | 1 | 22 | 2 | 1 | 6 | 1 | 1.5 | 0.5 | 2 | 2 | 0.35 | 0.2 | 4 | 0.1 |
| | | | | | | | | | | | | | | | | | | | | |
| Criteria A | | 4 | 2 | 2 | 2 | 1 | 1 | 2 | 4 | 4 | 4 | 1 | 2 | 4 | 2 | 2 | 3 | 3 | 4 | 3 |
| Criteria B | | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| Criteria C | | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 2 | 1 | 3 | 6 | 6 | 1 | 2 | 3 | 3 |
| Criteria D | | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| Criteria E | | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| Criteria F | | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 |

Criteria A, Type of Technology: 1 = Airframe, 2 = Flight Systems, 3 = Ground Systems, 4 = Propulsion
Criteria B, Enabling Technology Needed: 0 = No, 1 = Yes
Criteria C, Primary Goal/Benefit: 1 = Cost Reduction, 2 = Safety, 3 = Performance
Criteria D, Focused Program: 0 = No, 1 = Yes
Criteria E, New Product Needed: 0 = No, 1 = Yes
Criteria F, NASA Tesgint: 0 = No, 1 = Yes

**Table 3.1 - 3 Time Required for 12 NASA Technologies to Make Transition from TRLs 1 through 8 to TRL 9**

| Name of Technology | Electro Expulsive DeIcing | Engine Monitoring Systems | Flow Visualization | GA Wing | Supercritical Wing | Tiltrotor Technology | Graphite Fiber Stator Vane Bushings (Tribology) | Propfan Development | Fly-by-Light | Particulate Imaging Velocimetry | Surface Movement Advisor | Runway Grooves |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years to TRL 9 from TRL: | | | | | | | | | | | | |
| 1 | 16 | 8 | 13 | 14 | 20 | 47 | 16 | 18 | 25 | 13 | 3.4 | 4 |
| 2 | 16 | 8 | 7.5 | 13 | 18 | 44 | 14 | 16 | 23 | 11 | 2.6 | 3 |
| 3 | 15 | 7 | 6.5 | 13 | 17 | 43 | 12 | 15 | 18 | 7.4 | 2.3 | 3 |
| 4 | 14 | 7 | 3 | 12 | 16 | 42 | 9.7 | 13 | 10 | 4.9 | 2 | 3 |
| 5 | 13 | 6 | 2 | 9 | 15 | 41 | 7.8 | 11 | 6 | 1.9 | 1.65 | 3 |
| 6 | 12 | 5 | 1.5 | 8.5 | 14 | 19 | 5.8 | 9.5 | 4.5 | 1.4 | 1.3 | 3 |
| 7 | 6 | 5 | 1 | 7 | 13 | 11 | 3.9 | 7 | 3 | 0.6 | 1.3 | 2 |
| 8 | 5.5 | 0 | 0.5 | 4 | 1 | 11 | 1.9 | 1 | 1.5 | 0.3 | 0.1 | 1 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | | | |
| Criteria A | 2 | 2 | 2 | 1 | 1 | 2 | 4 | 4 | 2 | 4 | 3 | 3 |
| Criteria B | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| Criteria C | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 1 | 3 | 1 | 2 |
| Criteria D | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| Criteria E | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| Criteria F | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |

Criteria A, Type of Technology: 1 = Airframe, 2 = Flight Systems, 3 = Ground Systems, 4 = Propulsion
Criteria B, Enabling Technology Needed: 0 = No, 1 = Yes
Criteria C, Primary Goal/Benefit: 1 = Cost Reduction, 2 = Safety, 3 = Performance
Criteria D, Focused Program: 0 = No, 1 = Yes
Criteria E, New Product Needed: 0 = No, 1 = Yes
Criteria F, NASA Tesgint: 0 = No, 1 = Yes

**Table 3.1 - 4 Time Required for 12 NASA Technologies to Make Transition from one TRL to the Next TRL, up to TRL 9**

| Name of Technology | | Electro Expulsive DeIcing | Engine Monitoring Systems | Flow Visualization | GA Wing | Supercritical Wing | Tiltrotor Technology | Graphite Fiber Stator Vane Bushings (Tribology) | Propfan development | Fly-by-Light | Particulate Imaging Velocimetry | Surface Movement Advisor | Runway Grooves |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | | | | | | | | | | | | | |
| from TRL | to TRL | | | | | | | | | | | | |
| 1 | 2 | 0.5 | 1 | 5 | 0.5 | 1.5 | 3 | 1.9 | 2.5 | 2.5 | 2 | 0.8 | 1 |
| 2 | 3 | 0.5 | 1 | 1 | 0.5 | 1 | 1 | 1.9 | 1 | 5 | 4 | 0.3 | 0 |
| 3 | 4 | 1 | 1 | 3.5 | 0.5 | 1 | 1 | 1.9 | 1.5 | 7.5 | 2.5 | 0.3 | 0 |
| 4 | 5 | 1 | 1 | 1 | 3 | 1 | 1 | 1.9 | 2.5 | 4 | 3 | 0.3 | 0 |
| 5 | 6 | 1 | 1 | 0.5 | 0.5 | 1 | 22 | 1.9 | 1 | 1.5 | 0.5 | 0.3 | 0 |
| 6 | 7 | 6 | 0 | 0.5 | 1.5 | 1 | 8 | 1.9 | 2.5 | 1.5 | 0.8 | 0 | 1 |
| 7 | 8 | 0.5 | 5 | 0.5 | 3 | 12 | 0 | 1.9 | 6 | 1.5 | 0.3 | 1.2 | 1 |
| 8 | 9 | 5.5 | 0 | 0.5 | 4 | 1 | 11 | 1.9 | 1 | 1.5 | 0.3 | 0.1 | 1 |
| | | | | | | | | | | | | | |
| Criteria A | | 2 | 2 | 2 | 1 | 1 | 2 | 4 | 4 | 2 | 4 | 3 | 3 |
| Criteria B | | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| Criteria C | | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 1 | 3 | 1 | 2 |
| Criteria D | | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 |
| Criteria E | | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| Criteria F | | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |

Criteria A, Type of Technology: 1 = Airframe, 2 = Flight Systems, 3 = Ground Systems, 4 = Propulsion
Criteria B, Enabling Technology Needed: 0 = No, 1 = Yes
Criteria C, Primary Goal/Benefit: 1 = Cost Reduction, 2 = Safety, 3 = Performance
Criteria D, Focused Program: 0 = No, 1 = Yes
Criteria E, New Product Needed: 0 = No, 1 = Yes
Criteria F, NASA Tesgint: 0 = No, 1 = Yes

The individual technology maturation trajectories reported in the data tables above were based on survey interviews that sometimes were only able to provide limited and somewhat subjective data on the precise date a technology moved from one TRL to another. Where necessary, transition times were interpolated—as, for example, in a case when an interview subject identified a date at which a technology reached, say, TRL 3, and a date at which it reached TRL 5, but no date for TRL 4. On other occasions, estimates were made when, for example, a technology was said to reach TRL 6 in 1994, and to reach TRL 7 also in 1994. In such a case, TRL 6 would have been given the date 1994, and TRL 7 would be given a date half a year later (1994.5). The survey interview forms collected in appendix B can be used to assess the degree of interpolation and/or estimation that was required to develop a trajectory for any given technology in the tabulated data.

## 3.1 Analysis of Results

The TRL transition time results from the technology surveys were used to develop both overall average TRL chronologies and averages within significant subgroups of the sample.

## 3.2 Maturation from TRL 1 to TRL 9: Overall Sample Statistics

Overall maturation trends for NASA-developed technologies are depicted in **Error! Reference source not found.** which reports average time and standard deviations for the time taken to mature from any given TRL to TRL 9.

**Table 3.2 - 1 Sample Statistics for Twelve NASA Technologies Maturing from TRL 1 to TRL 9**

| Years to TRL 9 from TRL: | Average (years) | Standard Deviation |
|---|---|---|
| 1 | 16.3 | 11.4 |
| 2 | 14.5 | 10.9 |
| 3 | 13.1 | 10.6 |
| 4 | 11.3 | 10.6 |
| 5 | 9.7 | 10.7 |
| 6 | 7.0 | 5.6 |
| 7 | 5.0 | 3.9 |
| 8 | 2.2 | 3.1 |
| 9 | 0.0 | 0.0 |

The average, plus and minus the standard deviation, the longest single maturation trajectory (Tiltrotor Technology), and the quickest maturation trajectory (Surface Movement Advisor) are shown in **Error! Reference source not found.**, along with the average maturation trajectory. As **Error! Reference source not found.** and the **Error! Reference source not found.** illustrate, on average there is a fairly smooth transition pattern from TRL to TRL, although there is considerable variability within the sample.

## 3.3 Transition from TRL 1 to TRL 9: Sample Subgroup Statistics

While the average and overall variability of maturation trajectories is a primary focus of this task, the maturation patterns within well-defined subsets of the sample of technologies is also of interest. Table 3.3 - 1 and Table 3.3 - 2 depict differences between maturation trends for technologies according to the technology type: Airframe, Flight Systems, Ground Systems, or Propulsion. Ground System technologies have matured more rapidly than the other types of technology, although the Ground Systems subsample is small (two technologies).

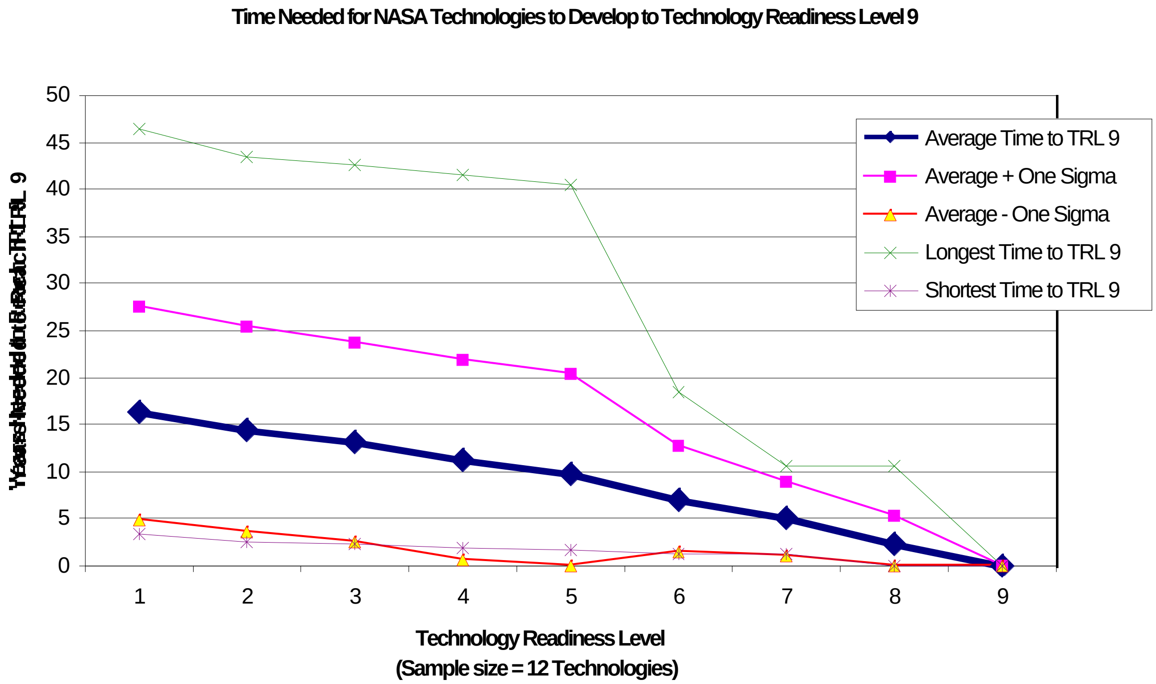


**Figure 3.2 - 1 Transition Trajectory Statistics, TRL 1 to TRL 9, for Twelve NASA Technologies**

**Table 3.3 - 1 Sample Statistics for Twelve NASA Technologies Making Transition from TRL 1 to TRL 9, by Type of Aeronautics Technology – Airframe and Flight Systems**

| Years to TRL 9 | Airframe Technologies (2) | | Flight System Technologies (5) | |
|---|---|---|---|---|
| from TRL: | Average | St Dev | Average | St Dev |
| 1 | 16.5 | 4.2 | 21.6 | 15.3 |
| 2 | 15.5 | 3.5 | 19.3 | 14.9 |
| 3 | 14.8 | 3.2 | 17.7 | 14.7 |
| 4 | 14.0 | 2.8 | 15.0 | 15.4 |
| 5 | 12.0 | 4.2 | 13.5 | 15.6 |
| 6 | 11.3 | 3.9 | 8.3 | 6.9 |
| 7 | 10.0 | 4.2 | 5.1 | 3.6 |
| 8 | 2.5 | 2.1 | 3.6 | 4.4 |
| 9 | 0 | 0 | 0.0 | 0.0 |

**Table 3.3 - 2 Sample Statistics for Twelve NASA Technologies Making Transition from TRL 1 to TRL 9, by Type of Aeronautics Technology – Ground Systems and Propulsion**

| Years to TRL 9 from TRL: | Ground System Technologies (2) | | Propulsion Technologies (3) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 | 3.7 | 0.4 | 15.6 | 2.3 |
| 2 | 3.0 | 0.5 | 13.5 | 2.1 |
| 3 | 2.7 | 0.6 | 11.2 | 3.6 |
| 4 | 2.5 | 0.6 | 9.2 | 4.1 |
| 5 | 2.2 | 0.7 | 6.7 | 4.4 |
| 6 | 1.9 | 0.8 | 5.6 | 4.1 |
| 7 | 1.4 | 0.1 | 3.8 | 3.2 |
| 8 | 0.3 | 0.3 | 1.1 | 0.8 |
| 9 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 3.3 - 3 shows maturation patterns for technologies with different program goals or benefit type. On average, technologies focused on safety benefits have matured more quickly than technologies intended to reduce costs or improve performance, although the subsample within the safety grouping is quite small.

**Table 3.3 - 3 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 9, by Program Goal or Primary Benefit**

| Years to TRL 9 from TRL: | Cost Reducing Technologies (3) | | Safety Technologies (2) | | Performance Technologies (7) | |
|---|---|---|---|---|---|---|
| | Average | St Dev | Average | St Dev | Average | St Dev |
| 1 | 15.5 | 11.0 | 6.0 | 2.8 | 19.6 | 12.1 |
| 2 | 13.5 | 10.1 | 5.4 | 3.0 | 15.6 | 13.6 |
| 3 | 11.4 | 8.1 | 5.0 | 2.8 | 14.4 | 13.7 |
| 4 | 8.3 | 5.7 | 4.7 | 2.5 | 13.1 | 13.9 |
| 5 | 6.1 | 4.4 | 4.4 | 2.3 | 11.6 | 14.0 |
| 6 | 5.1 | 4.1 | 3.8 | 1.8 | 8.0 | 7.2 |
| 7 | 3.8 | 2.9 | 3.3 | 2.5 | 5.4 | 5.1 |
| 8 | 0.9 | 0.7 | 0.3 | 0.4 | 3.1 | 3.9 |
| 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 3.3 - 4 and Table 3.3 - 5 report statistics for sub-samples of the technologies based on sorting criteria that were addressed during the survey interviews. The

relevant comparison is to the overall sample average, shown in **Error! Reference source not found.**. For

**Table 3.3 - 4 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 9 – Focused Program/NASA Tested Technologies**

| Years to TRL 9 from TRL: | Focused Program Technologies (4) | | NASA Tested Technologies (10) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 | 23.2 | 17.9 | 16.4 | 12.6 |
| 2 | 21.0 | 17.1 | 14.5 | 12.0 |
| 3 | 19.2 | 16.9 | 13.0 | 11.7 |
| 4 | 16.6 | 17.2 | 11.2 | 11.7 |
| 5 | 14.7 | 17.6 | 9.5 | 11.7 |
| 6 | 8.5 | 7.5 | 6.7 | 5.9 |
| 7 | 5.5 | 4.1 | 5.0 | 4.3 |
| 8 | 3.3 | 4.9 | 1.9 | 3.2 |
| 9 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table 3.3 - 5 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 9 – Requiring Enabling or New Technologies**

| Years to TRL 9 | Technologies Needing Enabling Technologies (8) | | Technologies Needing New Products (8) | |
|---|---|---|---|---|
| from TRL: | Average | St Dev | Average | St Dev |
| 1 | 13.2 | 7.1 | 17.9 | 12.5 |
| 2 | 11.4 | 6.7 | 16.0 | 12.1 |
| 3 | 9.9 | 5.8 | 14.8 | 12.2 |
| 4 | 7.7 | 5.0 | 13.4 | 12.5 |
| 5 | 5.8 | 4.5 | 11.8 | 12.7 |
| 6 | 5.2 | 4.3 | 8.5 | 6.3 |
| 7 | 3.4 | 2.8 | 5.8 | 4.6 |
| 8 | 1.7 | 2.0 | 2.9 | 3.6 |
| 9 | 0.0 | 0.0 | 0.0 | 0.0 |

example, the relatively few technologies that were developed as part of NASA focused programs took longer, on average, to reach a TRL of 9 than did the overall sample of technologies reaching a TRL of 9.

## 3.4 Transition Times between TRLs, for Technologies Reaching TRL 9: Overall Statistics Sample

Overall transition times from TRL to TRL for NASA-developed technologies are shown in Table 3.4 - 1 which reports average time and standard deviations for the time taken to move from one TRL to the next for those technologies that were identified as having reached TRL 9.

**Table 3.4 - 1 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies That Reached TRL 9**

| Years to Move from | Average | Standard Deviation |
|---|---|---|
| TRL 1 to TRL 2 | 1.8 | 1.4 |
| TRL 2 to TRL 3 | 1.4 | 1.5 |
| TRL 3 to TRL 4 | 1.8 | 2.0 |
| TRL 4 to TRL 5 | 1.6 | 1.2 |
| TRL 5 to TRL 6 | 2.6 | 6.1 |
| TRL 6 to TRL 7 | 2.1 | 2.5 |
| TRL 7 to TRL 8 | 2.7 | 3.5 |
| TRL 8 to TRL 9 | 2.2 | 3.1 |

The average, plus and minus the standard deviation, the longest single maturation trajectory (Tiltrotor Technology), and the quickest maturation trajectory (Surface Movement Advisor) are shown in Figure 3.4 - 1 along with the average TRL to TRL transition trajectory. As Table 3.4 - 1and Figure 3.4 - 1 illustrate, on average there is a fairly smooth transition pattern from TRL to TRL, although there is considerable variability within the sample. The figure also illustrates that the longest overall maturation path to TRL 9 – Tiltrotor Technology – is characterized by three exceptionally long TRL to TRL transitions, and is otherwise not unusual in this respect.

## 3.5 Transition Times between TRLs for Technologies Reaching TRL 9: Sample Subgroup Statistics

The tables in this section depict the TRL to TRL transitions for various subsamples and partitions of the entire technology dataset. While the average and overall variability of maturation trajectories is a primary focus of this task, the maturation patterns within well-defined subsets of the sample of technologies is also of interest.

Table 3.5 - 1 and Table 3.5 - 2 show TRL to TRL transition patterns for technologies of different types, while Table 3.5 - 3 shows maturation patterns for technologies with different program goals or benefit type, from the perspective of TRL to TRL transition rates. On average, Ground System technologies, and safety technologies, have moved through the TRL stages more rapidly than technologies intended to reduce costs or improve performance, although the subsamples within both of these groupings is quite small.

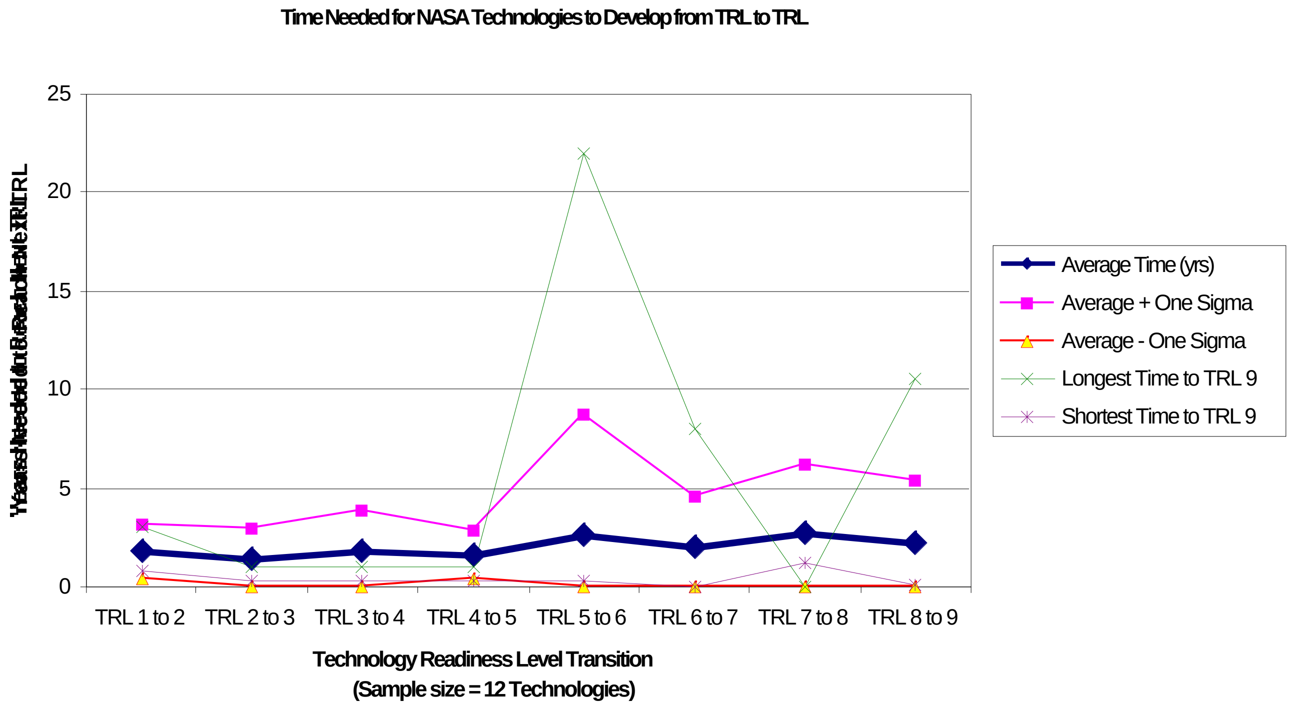


**Figure 3.4 - 1 Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9**

**Table 3.5 - 1 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Technology Type – Airframe and Flight Systems**

| Years from | Airframe Technologies (2) | | Flight System Technologies (5) | |
|---|---|---|---|---|
| TRL to TRL | Average | St Dev | Average | St Dev |
| 1 to 2 | 1.0 | 0.7 | 2.3 | 1.9 |
| 2 to 3 | 0.8 | 0.4 | 1.6 | 1.9 |
| 3 to 4 | 0.8 | 0.4 | 2.7 | 2.9 |
| 4 to 5 | 2.0 | 1.4 | 1.5 | 1.4 |
| 5 to 6 | 0.8 | 0.4 | 5.2 | 9.4 |
| 6 to 7 | 1.3 | 0.4 | 3.2 | 3.6 |
| 7 to 8 | 7.5 | 6.4 | 1.5 | 2.0 |
| 8 to 9 | 2.5 | 2.1 | 3.6 | 4.4 |

**Table 3.5 - 2 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Technology Type – Ground Systems and Propulsion**

| Years from TRL to TRL | Ground System Technologies (2) | | Propulsion Technologies (3) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 to 2 | 0.8 | 0.1 | 2.1 | 0.3 |
| 2 to 3 | 0.3 | 0.1 | 2.3 | 1.5 |
| 3 to 4 | 0.3 | 0.1 | 2.0 | 0.5 |
| 4 to 5 | 0.3 | 0.1 | 2.5 | 0.5 |
| 5 to 6 | 0.3 | 0.1 | 1.1 | 0.7 |
| 6 to 7 | 0.5 | 0.7 | 1.7 | 0.9 |
| 7 to 8 | 1.1 | 0.1 | 2.7 | 2.9 |
| 8 to 9 | 0.3 | 0.3 | 1.1 | 0.8 |

**Table 3.5 - 3 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Program Goal or Primary Benefit**

| Years from TRL to TRL | Cost Reducing Technologies (3) | | Safety Technologies (2) | | Performance Technologies (7) | |
|---|---|---|---|---|---|---|
| | Average | St Dev | Average | St Dev | Average | St Dev |
| 1 to 2 | 1.9 | 1.0 | 0.6 | 0.1 | 2.1 | 1.6 |
| 2 to 3 | 2.1 | 2.5 | 0.4 | 0.2 | 1.4 | 1.2 |
| 3 to 4 | 3.1 | 3.9 | 0.3 | 0.2 | 1.6 | 1.1 |
| 4 to 5 | 2.3 | 1.8 | 0.4 | 0.2 | 1.7 | 0.9 |
| 5 to 6 | 0.9 | 0.6 | 0.6 | 0.6 | 3.9 | 8.0 |
| 6 to 7 | 1.3 | 1.3 | 0.5 | 0.7 | 2.8 | 3.0 |
| 7 to 8 | 2.9 | 2.7 | 3.0 | 2.8 | 2.6 | 4.3 |
| 8 to 9 | 0.9 | 0.7 | 0.3 | 0.4 | 3.4 | 3.7 |

Table 3.5 - 4 and Table 3.5 - 5 report TRL to TRL transition time statistics for sub-samples of the technologies based on sorting criteria that were raised during the survey interviews. The most relevant comparison is to the overall sample average, shown in Table 3.4 - 1 and Figure 3.4 - 1 above. For example, the relatively few technologies that were developed as part of NASA focused programs took longer, on average, to move from TRL to TRL than did the overall sample of technologies reaching a TRL of 9.

**Table 3.5 - 4 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, by Focused Program/NASA Tested Technologies**

| Years from TRL to TRL | Focused Program Technologies (4) | | NASA Tested Technologies (10) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 to 2 | 2.2 | 1.0 | 1.9 | 1.4 |
| 2 to 3 | 1.8 | 2.1 | 1.5 | 1.7 |
| 3 to 4 | 2.6 | 3.3 | 1.9 | 2.2 |
| 4 to 5 | 2.0 | 1.6 | 1.7 | 1.3 |
| 5 to 6 | 6.2 | 10.5 | 2.9 | 6.7 |
| 6 to 7 | 3.0 | 3.5 | 1.7 | 2.3 |
| 7 to 8 | 2.2 | 2.6 | 3.1 | 3.7 |
| 8 to 9 | 3.3 | 4.9 | 1.9 | 3.2 |

**Table 3.5 - 5 Sample Statistics for Transition Times between TRLs, for Twelve NASA Technologies that Reached TRL 9, for Technologies Requiring Enabling or New Technologies**

| Years from TRL to TRL | Technologies Needing Enabling Technologies (8) | | Technologies Needing New Products (8) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 to 2 | 1.8 | 1.8 | 2.0 | 1.5 |
| 2 to 3 | 1.6 | 1.9 | 1.2 | 1.2 |
| 3 to 4 | 2.1 | 2.5 | 1.4 | 1.1 |
| 4 to 5 | 1.9 | 1.4 | 1.6 | 1.1 |
| 5 to 6 | 0.7 | 0.4 | 3.3 | 7.5 |
| 6 to 7 | 1.7 | 1.9 | 2.7 | 2.8 |
| 7 to 8 | 1.8 | 1.9 | 2.9 | 4.2 |
| 8 to 9 | 1.7 | 2.0 | 2.9 | 3.6 |

## 3.6 Transition from TRL 1 to TRL 6: Overall Sample Statistics

Overall maturation trends for NASA-developed technologies are depicted in that reports average time and standard deviations for the time taken to mature from any given TRL to TRL 6. Shown in Table 3.6 - 1, along with the average maturation trajectory in Figure 3.6 - 1, are the average plus and minus the standard deviation, the longest single maturation trajectory (Tiltrotor Technology) and the quickest maturation trajectory (Runway Grooves). As the table and the figure illustrate, on average there is again a fairly smooth transition pattern from TRL to TRL, although there is considerable variability within the sample.

**Table 3.6 - 1 Sample Statistics for Eighteen NASA Technologies Making Transition from TRL 1 to TRL 6**

| Years to TRL 6 from TRL: | Average | Standard Deviation |
|---|---|---|
| 1 | 8.1 | 6.8 |
| 2 | 6.6 | 6.1 |
| 3 | 5.4 | 5.4 |
| 4 | 4.0 | 5.0 |
| 5 | 2.5 | 4.9 |
| 6 | 0.0 | 0.0 |

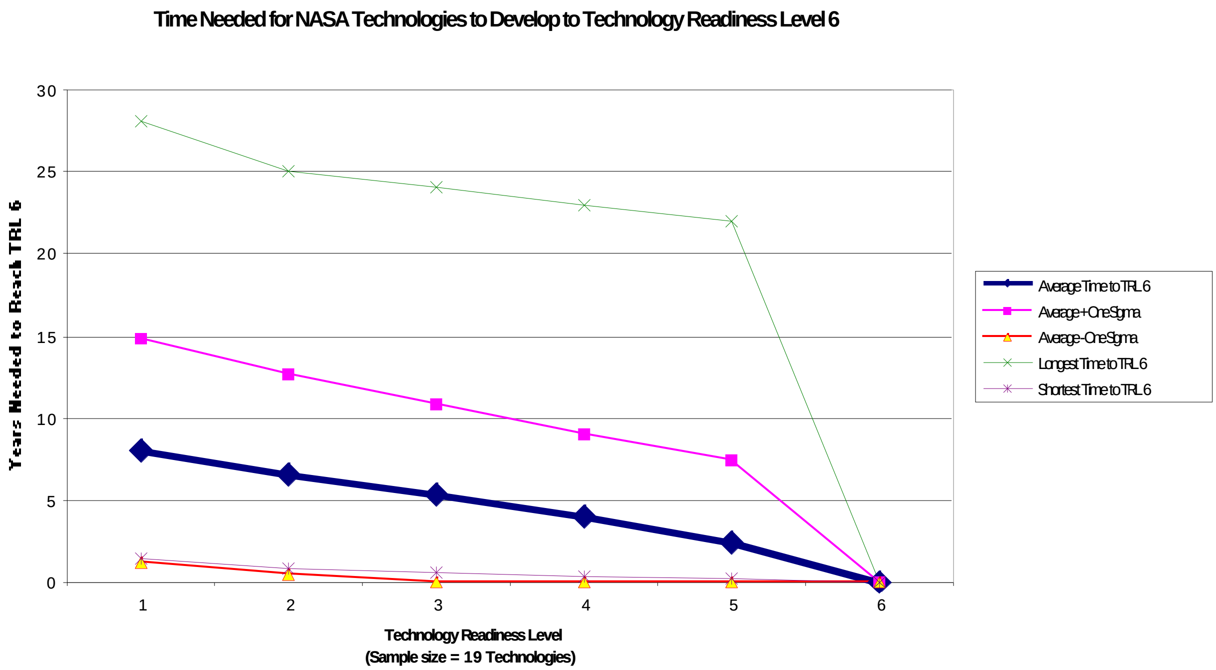


**Figure 3.6 - 1 Transition Trajectory Statistics, TRL 1 to TRL 6, for Eighteen NASA Technologies**

## 3.7 Transition from TRL 1 to TRL 6: Sample Subgroup Statistics

Differences within subsamples for the trends in the maturation of technologies from TRL 1 to TRL 6 have a pattern similar to that shown among technologies moving from TRL 1 to TRL 9. As shown in Table 3.7 - 1, Ground System technologies and, to a lesser extent, Airframe technologies moved from TRL 1 to TRL 6 more quickly on average than did the overall sample as well as the remaining subgroups, shown in Table 3.7 - 2 Flight Systems technologies and Propulsion technologies. As shown in Table 3.7 - 3, technologies with primarily safety benefits on average made it to TRL 6

**Table 3.7 - 1 Sample Statistics for Eighteen NASA Technologies Making Transition from TRL 1 to TRL 6, by Technology Type – Airframe and Flight Systems**

| Years to TRL 6 | Airframe Technologies (3) | | Flight System Technologies (7) | |
|---|---|---|---|---|
| from TRL: | Average | St Dev | Average | St Dev |
| 1 | 5.0 | 0.5 | 11.4 | 9.5 |
| 2 | 4.2 | 0.3 | 9.2 | 8.7 |
| 3 | 3.3 | 0.6 | 7.9 | 8.0 |
| 4 | 2.5 | 0.9 | 5.8 | 7.7 |
| 5 | 0.8 | 0.3 | 4.3 | 7.8 |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table 3.7 - 2 Sample Statistics for Eighteen NASA Technologies Making Transition from TRL 1 to TRL 6, by Technology Type – Ground Systems and Propulsion**

| Years to TRL 6 | Ground System Technologies (3) | | Propulsion Technologies (6) | |
|---|---|---|---|---|
| from TRL: | Average | St Dev | Average | St Dev |
| 1 | 1.7 | 0.3 | 8.8 | 4.1 |
| 2 | 1.2 | 0.3 | 7.3 | 3.7 |
| 3 | 1.0 | 0.4 | 5.7 | 3.0 |
| 4 | 0.8 | 0.4 | 4.2 | 2.6 |
| 5 | 0.2 | 0.1 | 2.3 | 2.5 |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table 3.7 - 3 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 6, by Program Goal or Primary Benefit**

| Years to TRL 6 from TRL: | Cost Reducing Technologies (3) | | Safety Technologies (4) | | Performance Technologies (10) | |
|---|---|---|---|---|---|---|
| | Average | St Dev | Average | St Dev | Average | St Dev |
| 1 | 10.4 | 9.3 | 2.7 | 1.3 | 9.8 | 7.8 |
| 2 | 8.4 | 8.6 | 2.2 | 1.4 | 8.2 | 7.0 |
| 3 | 6.3 | 6.1 | 1.7 | 1.1 | 7.0 | 6.8 |
| 4 | 3.2 | 2.4 | 1.3 | 0.7 | 5.6 | 6.9 |
| 5 | 0.9 | 0.6 | 0.6 | 0.5 | 4.0 | 7.1 |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

more quickly than did technologies that provided benefits primarily in the areas of cost reduction or performance improvement. Finally, Table 3.7 - 4 and Table 3.7 - 5 indicate that the pace of technology maturation does not, on average, differ much from the overall average trajectory from TRL 1 to TRL 6 for technologies that required development of enabling technologies or products for maturation, that required NASA testing, or were part of a NASA focused program.

**Table 3.7 - 4 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 6 – Focused Program/NASA Tested Technologies**

| Years to TRL 6 from TRL: | Focused Program Technologies (9) | | NASA Tested Technologies (12) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 | 10.9 | 8.3 | 8.9 | 8.0 |
| 2 | 9.2 | 7.6 | 7.2 | 7.2 |
| 3 | 7.9 | 7.0 | 5.9 | 6.5 |
| 4 | 6.1 | 6.7 | 4.3 | 6.1 |
| 5 | 4.4 | 6.8 | 2.6 | 6.1 |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table 3.7 - 5 Sample Statistics for NASA Technologies Making Transition from TRL 1 to TRL 6 – Requiring Enabling or New Technologies**

| Years to TRL 6 from TRL: | Technologies Needing Enabling Technologies (14) | | Technologies Needing New Products (12) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 | 9.2 | 7.5 | 8.6 | 6.9 |
| 2 | 7.5 | 6.8 | 6.8 | 6.2 |
| 3 | 6.2 | 6.1 | 5.8 | 6.0 |
| 4 | 4.6 | 5.7 | 4.5 | 6.0 |
| 5 | 3.0 | 5.7 | 3.0 | 6.1 |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 |

## 3.8 Transition Times between TRLs, for Technologies Reaching TRL 6 Overall Statistics Sample

The remaining Table 3.8 - 1, Table 3.9 - 1 through Table 3.9 - 5, and Figure 3.8 - 1 illustrate the trends in the paths of transition from TRL to TRL among those NASA technologies that were identified as reaching TRL 6.

**Table 3.8 - 1 Sample Statistics for Transition Times between TRLs, for Eighteen NASA Technologies That Reached TRL 6**

| Years to Move from | Average | Standard Deviation |
|---|---|---|
| TRL 1 to TRL 2 | 1.5 | 1.3 |
| TRL 2 to TRL 3 | 1.2 | 1.3 |
| TRL 3 to TRL 4 | 1.4 | 1.7 |
| TRL 4 to TRL 5 | 1.5 | 1.2 |
| TRL 5 to TRL 6 | 2.5 | 4.9 |

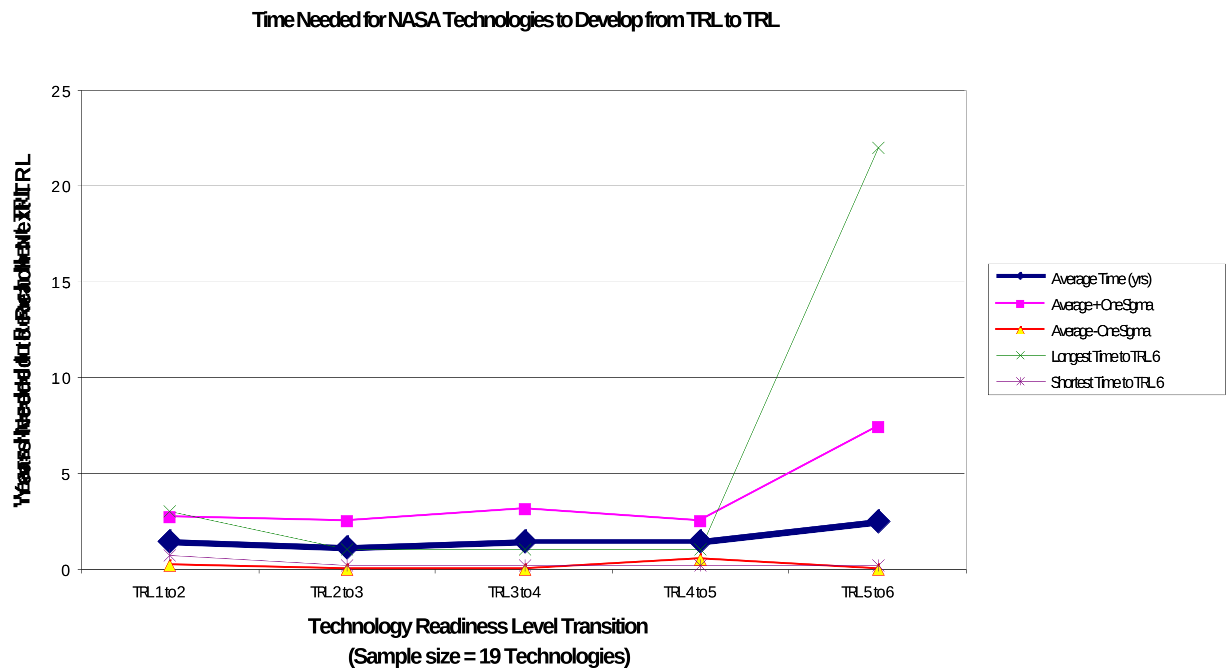


**Figure 3.8 - 1 TRL to TRL Transition Trajectory Statistics, TRL 1 to TRL 6, for Eighteen NASA Technologies**

## 3.9 Transition Times between TRLs for Technologies that reached TRL 6: Sample Subgroup Statistics

Differences within subsamples for the trends in the transition between TRLs among technologies that reached TRL 6 again have a pattern similar to that shown by the technologies that reached TRL 9. As shown in Table 3.9 - 1 and Table 3.9 - 2, Ground System and Airframe technologies that reached TRL 6 moved from TRL to TRL more quickly that did the overall sample or the remaining two subgroups.

**Table 3.9 - 1 Sample Statistics for TRL to TRL Trends for Eighteen NASA Technologies Reaching TRL 6, by Technology Type – Airframe and Flight Systems**

| Years from TRL to TRL: | Airframe Technologies (3) | | Flight System Technologies (7) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 to 2 | 0.8 | 0.6 | 2.1 | 1.8 |
| 2 to 3 | 0.8 | 0.3 | 1.3 | 1.6 |
| 3 to 4 | 0.8 | 0.3 | 2.1 | 2.6 |
| 4 to 5 | 1.7 | 1.2 | 1.5 | 1.2 |
| 5 to 6 | 0.8 | 0.3 | 4.3 | 7.8 |

**Table 3.9 - 2 Sample Statistics for TRL to TRL Trends for Eighteen NASA Technologies Reaching TRL 6, by Technology Type – Ground Systems and Propulsion**

| Years from TRL to TRL | Ground System Technologies (3) | | Propulsion Technologies (6) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 to 2 | 0.6 | 0.3 | 1.5 | 0.8 |
| 2 to 3 | 0.2 | 0.1 | 1.6 | 1.4 |
| 3 to 4 | 0.2 | 0.1 | 1.4 | 0.7 |
| 4 to 5 | 0.6 | 0.5 | 1.9 | 1.0 |
| 5 to 6 | 0.2 | 0.1 | 2.3 | 2.5 |

As shown in Table 3.9 - 3, technologies that made it to TRL 6 which have primarily safety benefits on average moved more rapidly from TRL to TRL than did those TRL 6 technologies that provided benefits primarily in the areas of cost reduction or performance improvement. Finally, Table 3.9 - 4 and Table 3.9 - 5 indicate that the pace of technology maturation, as expressed by the time taken to move from TRL to TRL, does not, on average, differ much from the overall average trajectory from TRL to TRL for technologies that required development of enabling technologies or products for maturation, that required NASA testing, or were part of a NASA focused program.

**Table 3.9 - 3 Sample Statistics for TRL to TRL Trends among Eighteen NASA Technologies Reaching TRL 6, by Program Goal or Primary Benefit**

| Years from TRL to TRL | Cost Reducing Technologies (3) | | Safety Technologies (4) | | Performance Technologies (10) | |
|---|---|---|---|---|---|---|
| | Average | St Dev | Average | St Dev | Average | St Dev |
| 1 to 2 | 1.9 | 1.0 | 0.5 | 0.1 | 1.7 | 1.5 |
| 2 to 3 | 2.1 | 2.5 | 0.5 | 0.3 | 1.2 | 1.1 |
| 3 to 4 | 3.1 | 3.9 | 0.5 | 0.3 | 1.4 | 1.0 |
| 4 to 5 | 2.3 | 1.8 | 0.6 | 0.3 | 1.6 | 0.8 |
| 5 to 6 | 0.9 | 0.6 | 0.6 | 0.5 | 4.0 | 7.1 |

**Table 3.9 - 4 Sample Statistics for TRL to TRL Trends among Eighteen NASA Technologies Reaching TRL 6 – Focused Program/NASA Tested Technologies**

| Years from TRL to TRL | Focused Program Technologies (9) | | NASA Tested Technologies (12) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 to 2 | 1.7 | 1.1 | 1.7 | 1.4 |
| 2 to 3 | 1.4 | 1.4 | 1.3 | 1.5 |
| 3 to 4 | 1.7 | 2.2 | 1.7 | 2.1 |
| 4 to 5 | 1.7 | 1.1 | 1.6 | 1.2 |
| 5 to 6 | 4.4 | 6.8 | 2.6 | 6.1 |

**Table 3.9 - 5 Sample Statistics for TRL to TRL Trends among Eighteen NASA Technologies Reaching TRL 6 – Technologies Requiring Enabling or New Technologies**

| Years from TRL to TRL | Technologies Needing Enabling Technologies (14) | | Technologies Needing New Products (12) | |
|---|---|---|---|---|
| | Average | St Dev | Average | St Dev |
| 1 to 2 | 1.7 | 1.4 | 1.7 | 1.4 |
| 2 to 3 | 1.3 | 1.4 | 1.1 | 1.0 |
| 3 to 4 | 1.6 | 1.9 | 1.2 | 0.9 |
| 4 to 5 | 1.6 | 1.1 | 1.6 | 0.9 |
| 5 to 6 | 3.0 | 5.7 | 3.0 | 6.1 |

# 4.0 FINDINGS AND IMPLICATIONS OF RESULTS FOR NASA SYSTEMS STUDIES

The statistical analysis by sample subgroups indicates that variability in NASA technology maturation patterns has some relationship to the type of technology, to the technology's primary goal or benefit, and, with less variability, to the additional technical or testing requirements related to the technology's development.

Although the present work effort does not consider the influence of research intensity, funding changes, and the socio-political environment on the development speed for any given technology, these issues do matter, and were often mentioned by survey interview subjects and other NASA personnel with whom the study team spoke. From a Systems Studies perspective, predicting socio-political and funding trends may be even more difficult than predicting technology maturation rates.

For NASA Systems Studies, the most important finding may be the shorter maturation time identified, on average, for technologies with a safety focus, and the longer maturation time identified for technologies aimed at reducing aviation costs and improving aviation performance. This is because projecting when an immature technology will begin providing actual benefits to the aviation industry and its customers depends precisely on when it will become available for use. This maturation time also affects the discounted present value of these hypothetical future benefits: the present value of a dollar of benefits is greater the sooner it becomes feasible.

A similar assessment holds for the somewhat shorter average maturation trajectories displayed by Ground Systems technologies, relative to Flight Systems technologies, Propulsion technologies, and, to a lesser extent, Airframe technologies. An important caveat is that the subsamples within each of these technology areas are often rather small.

There is little variation from the overall average trajectory within the subsamples of technologies that required an enabling technology or product to be developed, that required NASA testing, or were part of a NASA focused program. Additional research may provide greater insight into the relationships between these components of NASA technology development programs and specific maturation chronologies.

More generally, it should be noted that this study is unavoidably biased towards an analysis of the maturation and development "behaviors" of technologies that actually made it as far as TRL 6 or TRL 9. Because this retrospective study is conducted on this basis – assessing NASA's successes – there is a sample truncation problem that may limit the usefulness of the results as a prospective tool. To overcome this, it may be necessary both to increase the sample size of successful technologies examined and explicitly seek information on technology programs that may have seemed promising at an early point, but did not pan out.

However, the study team has also found that the notions of technology assessments based on "Technology Readiness Levels" and on trajectories of "technologies transitioning from TRL to TRL" was not widely familiar among the NASA research community, nor were these models uncontroversial. In particular, the earliest TRL levels (TRL 1 to TRL 3) seemed identical in the minds of several researchers to the basic science that underlies all of aeronautical and other physical research. As one person observed with respect to a propulsion technology development program, "Doesn't TRL 1 go back to Bernoulli?" It may be that the nature of scientific research, certainly at the basic research level, lacks sufficient structure for building a consensus model of how NASA research proceeds and succeeds.

It is the view of the study team, however, that this uncertainty does not mean that assessments of NASA research are not possible. It may mean that there may be payoffs from additional work toward developing a research assessment framework, based on the TRL technology maturation schema. Broader promulgation of the TRL framework within the NASA Aeronautics research community may itself provide valuable insights for refining it, both for the purposes of the Systems Analysis Branch and for other research assessment needs.

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# Appendix A – NASA Questionnaire

**TECHNOLOGY TRACKING FORM**
**TRL CASE STUDIES**

1. Team interviewer: ______________________________________________
   Date of interview: ______________________________________________

2. Name of technology: ____________________________________________
   Technology description: __________________________________________
   ________________________________________________________________
   ________________________________________________________________

3. NASA Center or Centers: _________________________________________
   NASA Contact(s): _______________________________________________
   ________________________________________________________________
   (Include names, phone and fax numbers and email addresses)

4. First Aeronautics Applications (include company, aircraft make and model, and specifics on application):
   ________________________________________________________________
   ________________________________________________________________

5. Other Early Aeronautics Applications: (include company, aircraft make and model, and specifics on application):
   ________________________________________________________
   ________________________________________________________________

6. Were any enabling or complementary technologies needed to apply this technology (explain)?
   ________________________________________________________
   ________________________________________________________________

7. What needs did this technology fulfill? How did the technology meet or address the identified needs?

   Cost reduction ___________________________________________________
   ________________________________________________________________

   Safety _________________________________________________________
   ________________________________________________________________

   Performance ____________________________________________________
   ________________________________________________________________

   Environmental compatibility ______________________________________
   ________________________________________________________________

   Regulatory compliance ___________________________________________
   ________________________________________________________________

Other ____________________________________________________________
____________________________________________________________________

8. a. When were you first aware of the concept underlying this technology? ____________

b. When were you first aware of the potential benefits that the application of this technology might produce? ______________________________________________

c. On the TRL scale below, where was the technology when you first became aware of the concept? _______________________ of the potential benefits? ______________

9. Technology Progression:

| | Level | Qualifier/Development Hurdle |
|---|---|---|
| Basic Research | 1 | Basic scientific/engineering principles observed and reported |
| Feasibility Research | 2 | Technology concept, application, and potential benefits formulated (candidate system selected) |
| Feasibility Research | 3 | Analytic and/or experimental proof-of-concept completed (proof of critical function or characteristic) |
| Technology Development | 4 | System concept observed in laboratory environment (breadboard test) |
| Technology Development | 5 | System concept tested and potential benefits substantiated in a controlled relevant environment |
| System Development | 6 | Prototype of system concept is demonstrated in a relevant environment |
| System Development | 7 | System prototype is tested and potential benefits substantiated more broadly in a relevant environment |
| Operational Verification | 8 | Actual System constructed and demonstrated, and benefits substantiated in a relevant environment |
| Operational Verification | 9 | Operational use of actual system tested, and benefits proven |

10. Was the technology advanced as part of a NASA focused program? Yes _____ No _____
If yes, which one(s) ___________________________________________________
____________________________________________________________________

11. Did the application of the technology have to wait for a new product to be developed? If yes, please explain. ___________________________________________________
____________________________________________________________________
____________________________________________________________________

12. Did the technology undergo flight or other testing by NASA?  If yes, describe tests and identify NASA facility were conducted. ______________________________

______________________________

______________________________

13. Are there any reports that describe the progression of this technology from its earliest conceptual formulation to its application by the aeronautics industry, or describe it progression through any parts of this sequence? ______________________________

______________________________

______________________________

______________________________

14. Do you have any other information (e.g., cost through TRLs, etc.)? ______________________________

______________________________

______________________________

______________________________

# Appendix B – Completed Questionnaires